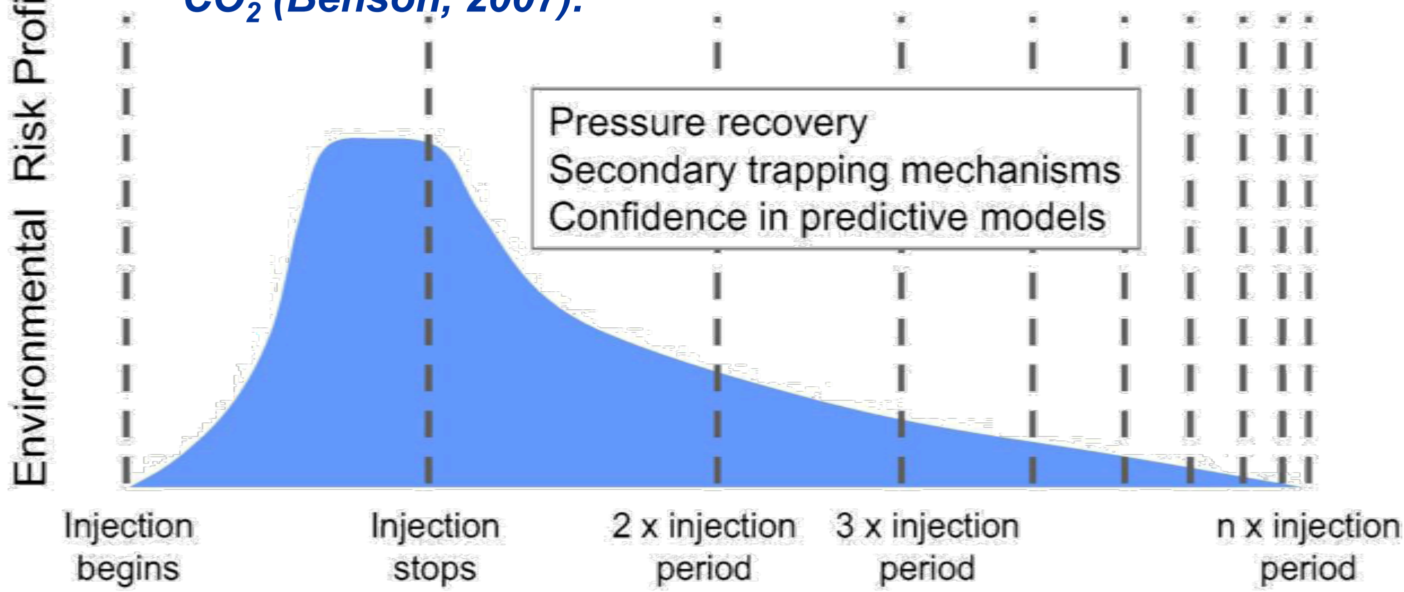
A successful storage project will require predicting the site's performance beyond the injection phase.

Schematic description of risk assuming probability of CO_2 release relates to reservoir pressure and phase-distribution of CO_2 (Benson, 2007).



Site Characterization | **Site Operation (e.g., CO_2-EOR)** | **Post Closure** | **Long-Term Stewardship**

10^0 10^1 10^2 10^3

Time (yrs)

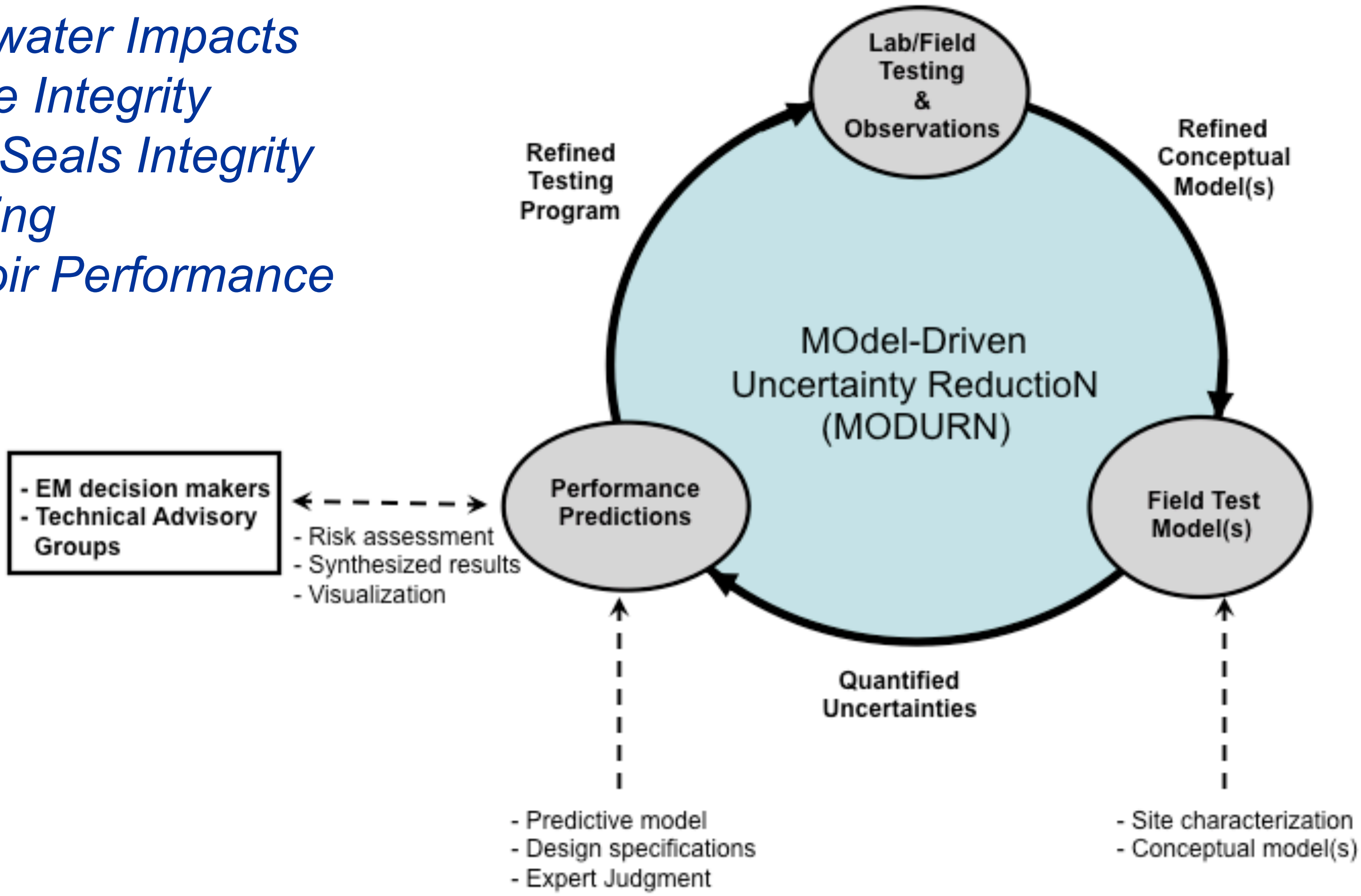
National Risk Assessment Program

Annual performance prediction

Updated with refined testing and conceptual models

Develop monitoring guidelines

Groundwater Impacts
Wellbore Integrity
Natural Seals Integrity
Monitoring
Reservoir Performance



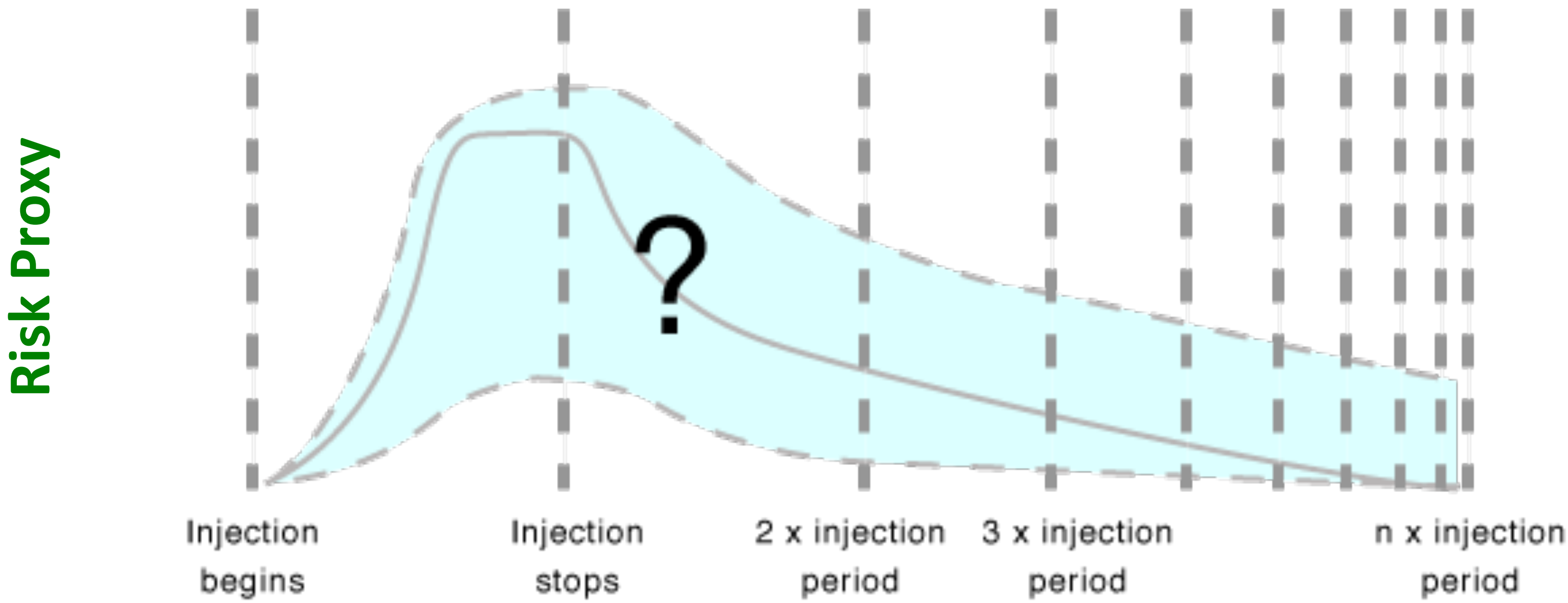
NRAP Goal: Develop quantitative site-specific risk profiles to calculate residual liability for long-term stewardship.

① pH (function of CO_2 only)

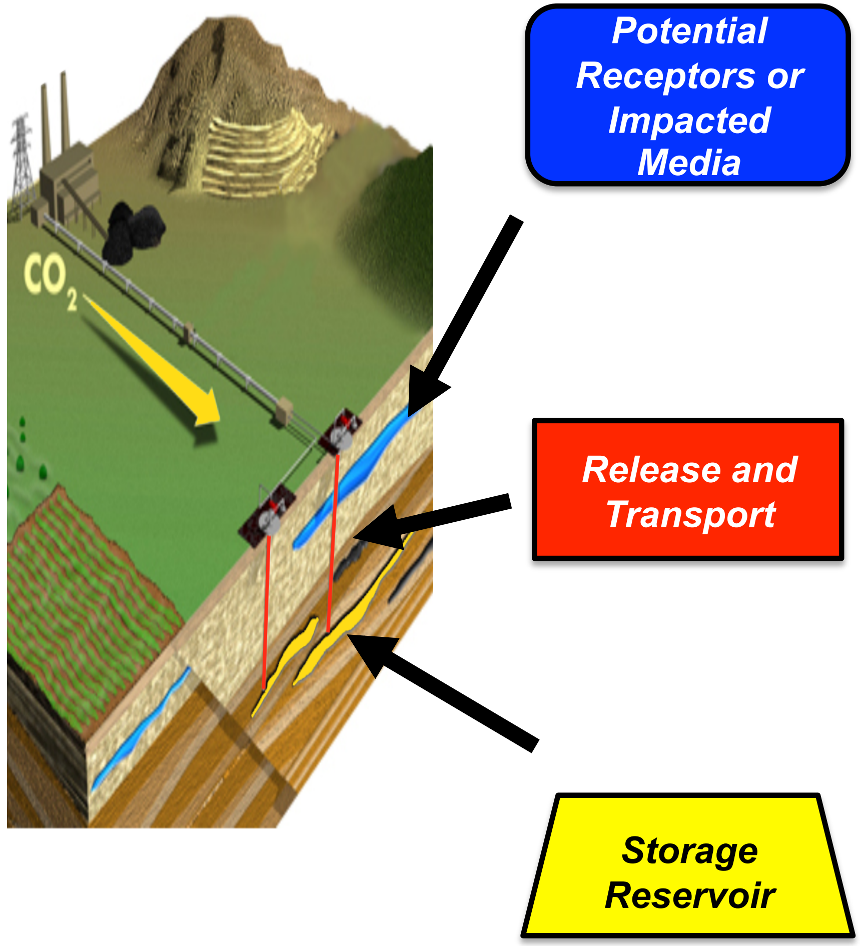
② TDS (function of both brine & CO_2)

③ return of CO_2 to the atmosphere

④ reservoir stress



Integrated Assessment Model for Risk Profiles in Groundwater Systems



CO_2/brine leakage rates used as boundary conditions in detailed reactive-flow models to calculate dynamic evolution of pH & TDS

- equilibrium-geochemistry, continuum-scale reactive flow; based on two real aquifers
  - High Plains aquifer in LLNL's NUFT
  - A Coastal Sandstone aquifer in LBNL's TOUGH2

Wellbore-release model used to calculate CO_2/ brine leakage rates based on predicted reservoir pressure and saturation

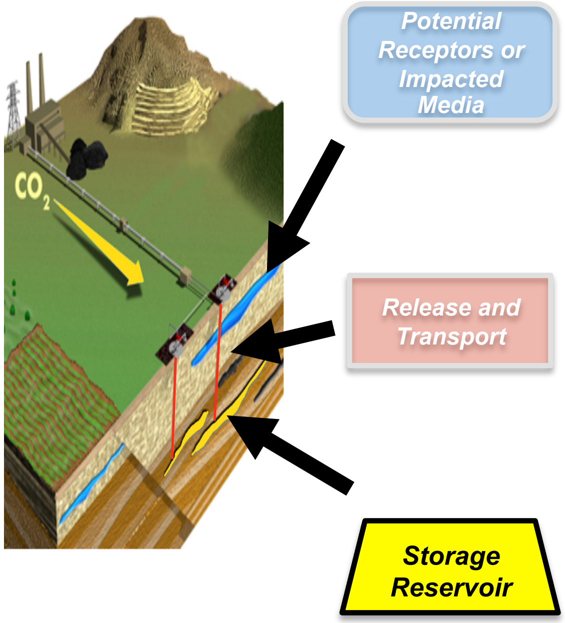
- abstraction based on continuum-scale multiphase-flow model plus Monte Carlo analysis
  - Multiple realizations using wellbore cement characteristics
  - CO_2/brine leak rates calculated in LANL's CO_2-PENS using abstraction for wellbore flow output from reservoir model

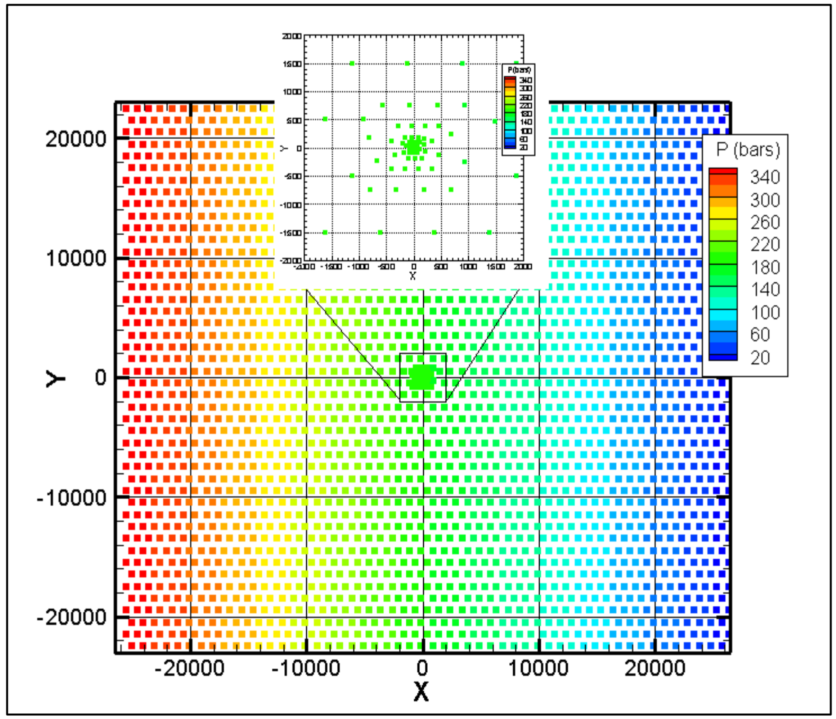
Detailed reservoir model used to predict pressure & saturation at reservoir–caprock interface

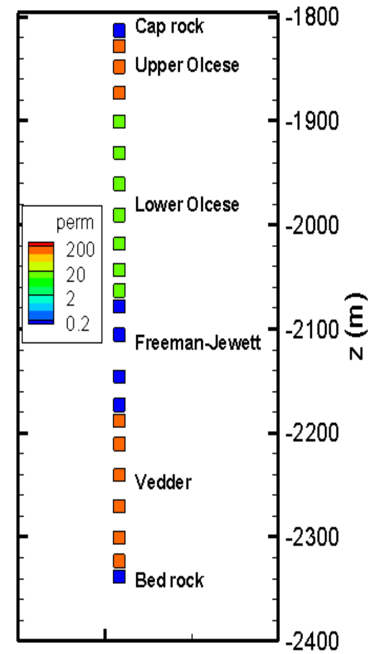
- continuum-scale multiphase-flow model
  - based on real site
  - used to predict CO_2:brine ratio (saturation), pressure

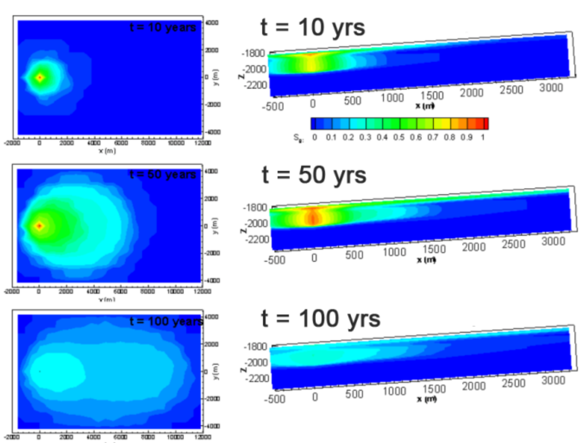
Approach assumes that mass traveled across sub-system boundary does not significantly affect mass balance within individual sub-systems.

Integration of reservoir behavior through continuum-scale reservoir model to predict pressures and saturations at bottom of caprock.









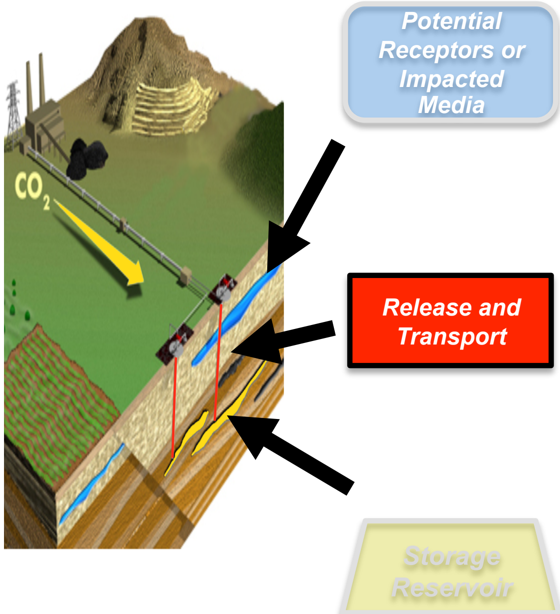
TOUGH2 model of potential storage formations at a site in the Southern San Joaquin Valley

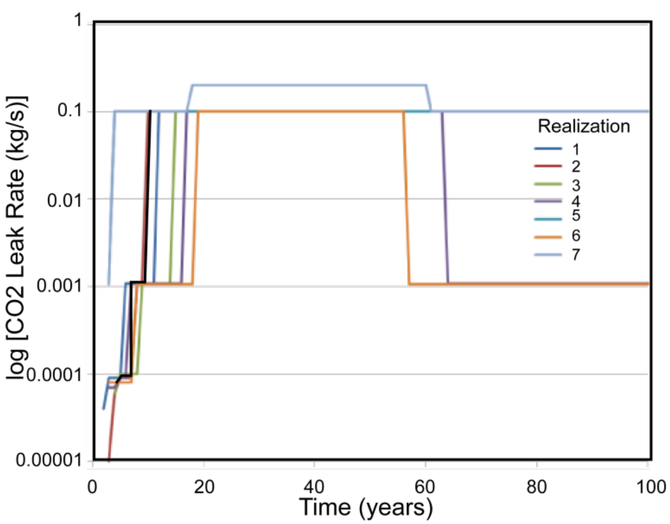
- Lateral extent 53 km by 46 km with 3.85º dip;
  22-layer model with total thickness = 540 m; depth 1805–2345 m
- Hydrostatic pressure (~220 bars at Vedder); geothermal temperature gradient (T=71 ºC at Vedder)

Injection of 1 million metric tons CO_2/yr for 50 yrs; followed reservoir evolution for 50 yrs post-closure

- Pressures & saturations at the top formation layer at 20 time intervals

Integration of release processes through wellbore-release model based on abstracted multiphase physics and assumed wellbore permeability.





Wellbore leak-rate was treated as a stochastic variable using Monte Carlo analysis

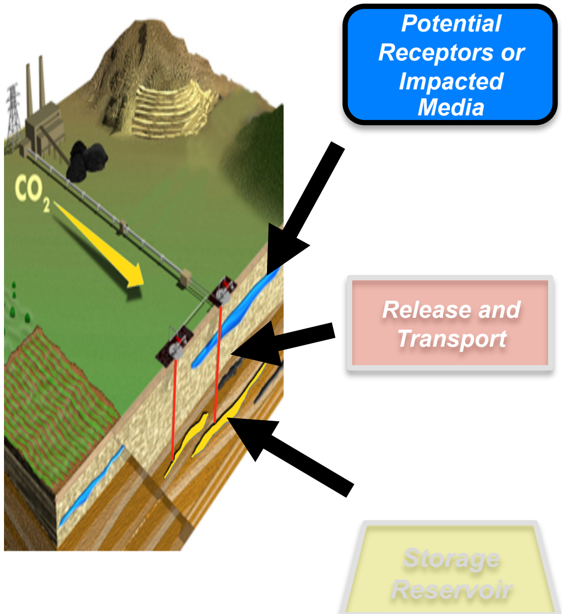
- Wellbore response surface generated from high-fidelity, multi-phase flow of CO_2/brine through wells using LANL's continuum-scale FEHM
  - Leak-rate variability was function of pressure, saturation, and permeabilities of reservoir, wellbore cement, and aquifer.
- Monte-Carlo methods using LANL's CO_2-PENS system model and wellbore response surface
- Coupling to storage reservoir via simulation results from TOUGH2 (time dependent pressure and saturation)

Wellbores were assumed to have spatial density of a typical EOR site (based on site in west Texas)

- 10 randomly distributed abandoned wells (injection well is not considered as potential flow path)
- 90% of wells with good (low permeability) cement; 10% wells with poor cement
- Values used for wellbore cements based on preliminary assessment of one available field data set
  - good cement permeability – 10^{-17} m^2 (10 μD)
  - poor cement permeability – 10^{-10} m^2 (100 D)

Time-dependent CO_2 & brine leakage rates into shallow aquifer were based on multiple (but limited) realizations

Integration of aquifer processes through equilibrium-geochemistry, continuum-scale, reactive-flow model.



Two different sets of calculations with two models

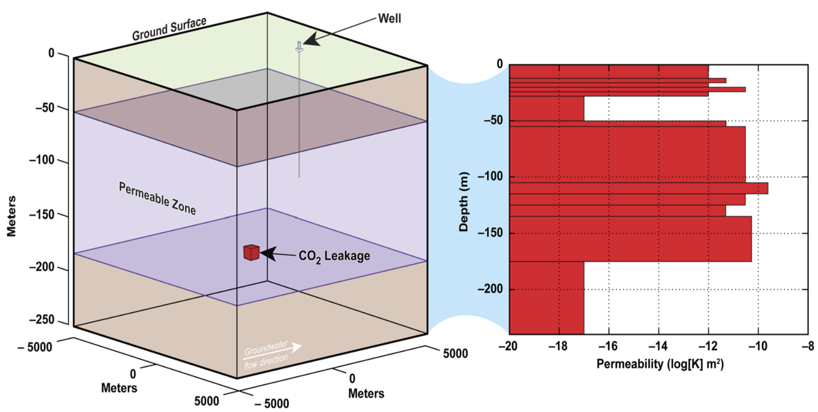
- High Plains aquifer using LLNL's NUFT (Caroll et al., 2009)
- Coastal sandstone aquifer using LBNL's TOUGH2 (Zheng et al, 2009)

Both models used time-dependent CO_2 & brine leakage rates as boundary conditions to predict time-dependent change in pH and TDS

Reactive transport calculations with assumed mineralogy and fluid compositions

- quartz-calcite aquifer; quartz-feldspar-clay aquifer

Background flow to account for regional groundwater flow

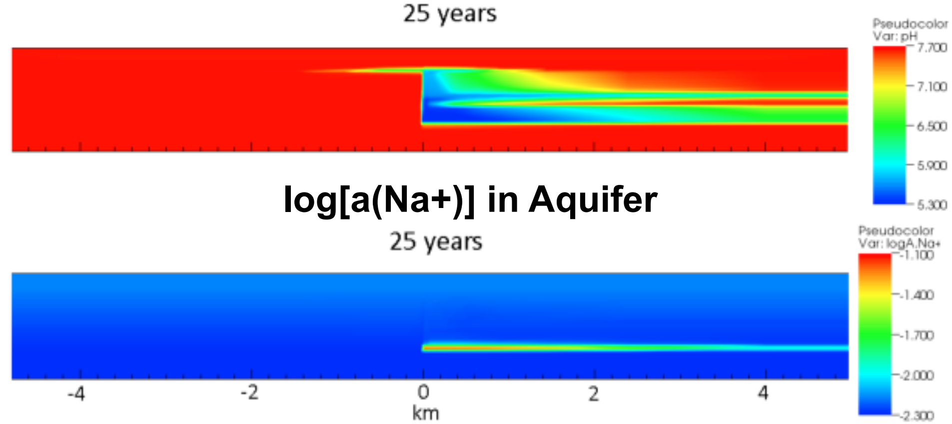


pH in Aquifer

25 years

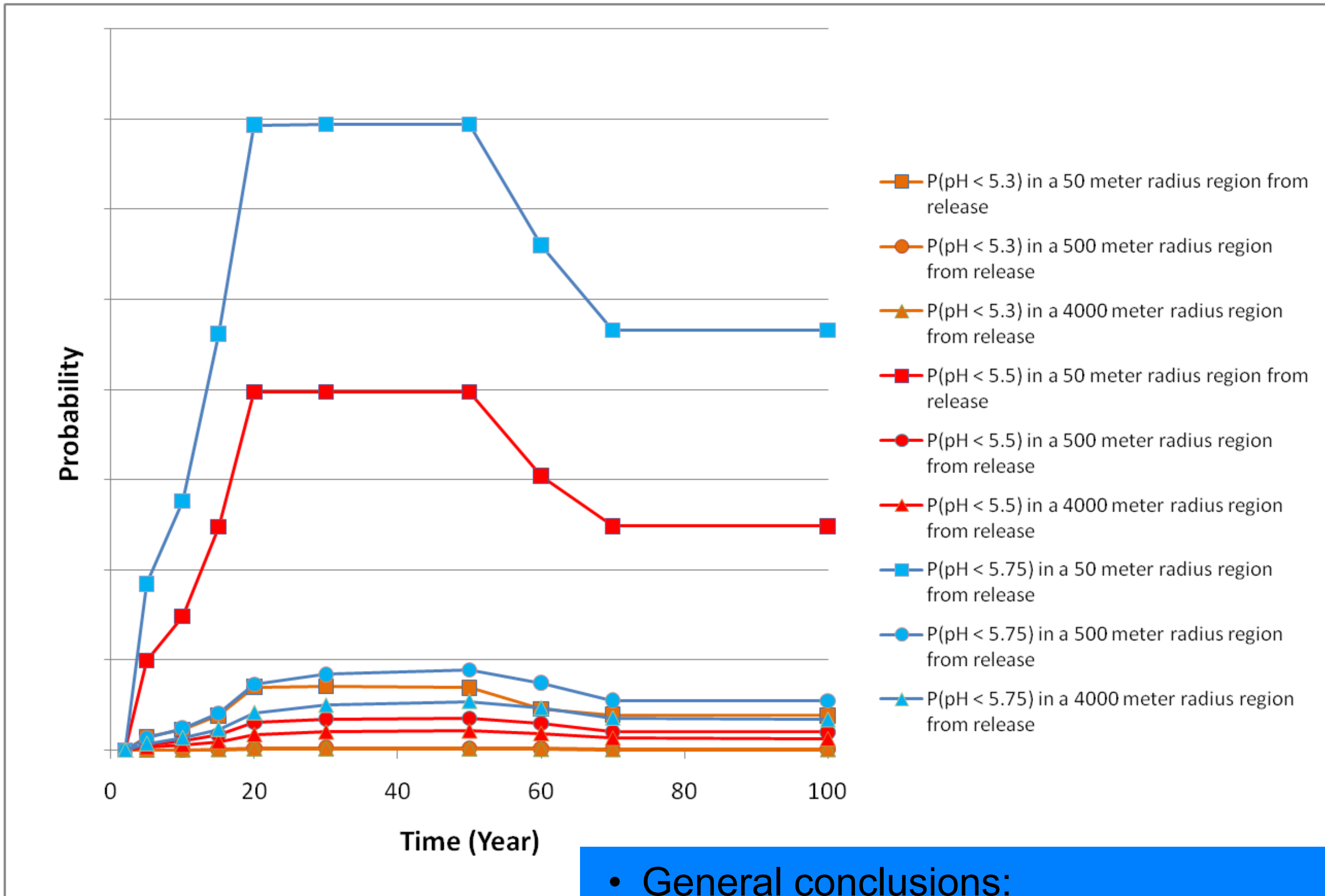
log[a(Na+)] in Aquifer

25 years



Preliminary Risk Profiles for pH in Groundwater System

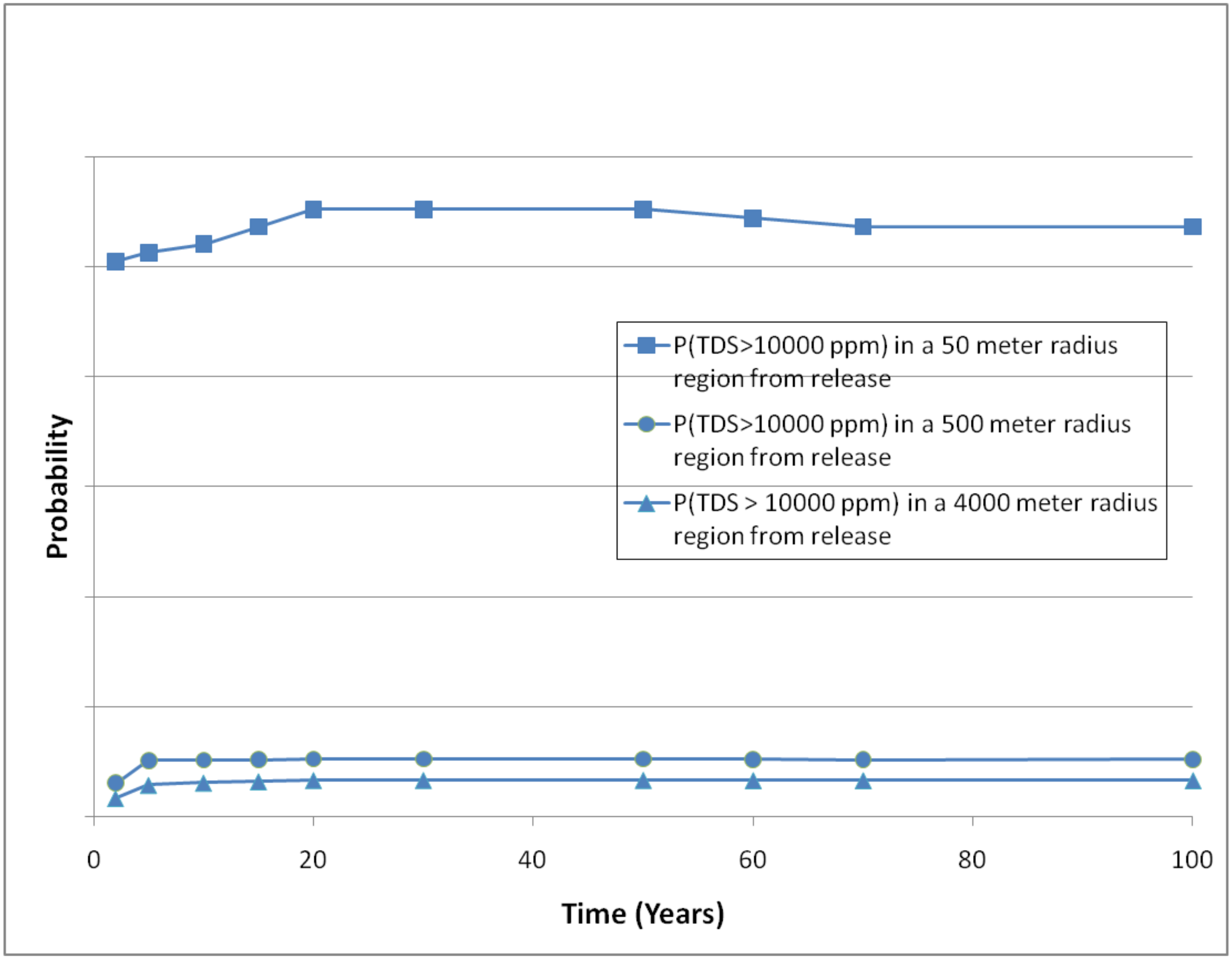
The profiles below show the probability that pH in a volume of certain radius centered around the leaky well decreases below different cutoffs



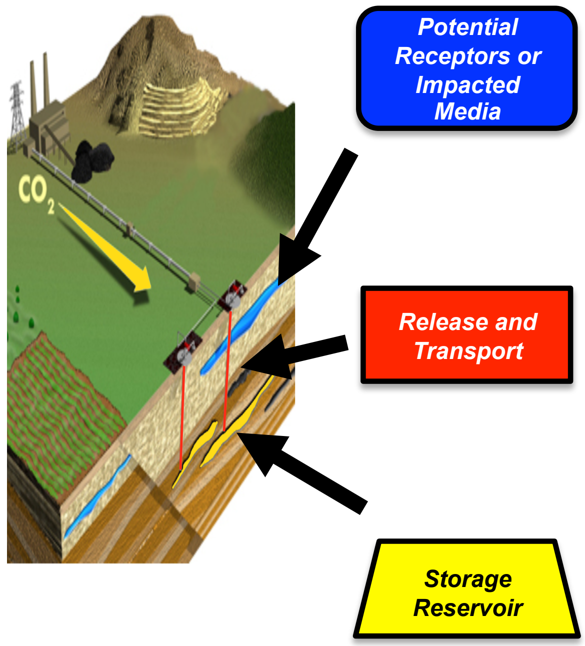
- General conclusions:
  - probability of pH impact goes down with distance from release point
  - recovery initiates after injection ceases but probability does not go down to zero

Preliminary Risk Profiles for TDS in Groundwater System

The profiles below show the probability that the concentration of Na^+ in a volume of certain radius centered around the leaky well increases above 10,000 ppm



Key Needs for First Generation Risk Profile Development



Receptors

- *Groundwater/Atmosphere*
  - perform systematic realizations across ranges in key parameters
  - develop robust abstractions of responses (e.g pH/TDS etc.) as functions of key parameters
  - develop robust protocol for integrating information to/from multiple simulators
  - evaluate assumption that mass transfer between sub-systems has negligible impact
- *Ground Motion*
  - develop robust numerical models for simulating ground deformation as function of stress changes
  - perform systematic realizations across ranges in key parameters
  - develop robust abstractions of responses as functions of key parameters
  - develop robust protocol for integrating information to/from multiple simulators

Release/Transport

- *Wellbores*
  - perform systematic realizations across ranges in key parameters
  - conduct robust analysis of effective wellbore permeabilities observed in various environments
  - develop time-varying permeability models
  - develop coupled geomechanics models to estimate change in permeability
- *Faults/Fractures*
  - perform systematic realizations across ranges in key parameters
  - conduct robust analysis of effective permeabilities for various types of seals
  - develop time-varying permeability models
  - develop coupled geomechanics models to estimate change in permeability

Storage Reservoirs

- *Pressure/Saturation/Stress*
  - develop robust protocols for passing information to/from multiple simulators
  - develop abstractions for pressure-saturation evolution for coupled flow-reaction-geomechanics